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Summary of Liquid Propulsion System Needs in Support of the Constellation Program

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Abstract

In January 2004, the President of the United States established the Vision for Space Exploration (VSE) to complete the International Space Station, retire the Space Shuttle and develop its replacement, and expand the human presence on the Moon as a stepping stone to human exploration of Mars and worlds beyond. In response, NASA developed the Constellation Program, consisting of the components shown in Figure 1. This paper will summarize the manned spaceflight liquid propulsion system needs in support of the Constellation Program over the next 10 years. It will address all liquid engine needs to support human exploration from low Earth orbit (LEO) to the lunar surface, including an overview of engines currently under contract, those baselined but not yet under contract, and those propulsion needs that have yet to be initiated. There may be additional engine needs for early demonstrators, but those will not be addressed as part of this paper. Also, other portions of the VSE architecture, including the planned Orion abort test boosters and the Lunar Precursor Robotic Program, are not addressed here as they either use solid motors or are focused on unmanned elements of returning humans to the Moon.

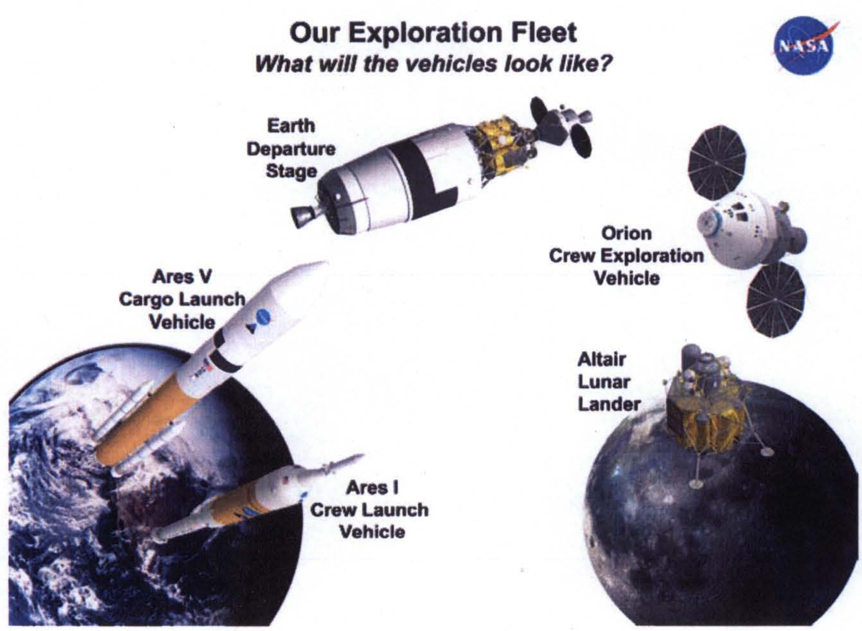

Figure 1. Constellation Program components

I. Introduction

In January 2004, the President of the United States established the Vision for Space Exploration (VSE) to complete the International Space Station, retire the Space Shuttle and develop its replacement, and expand human presence on the Moon as a stepping stone toward exploring Mars and worlds beyond. NASA's exploration plans are represented in Figure 2.

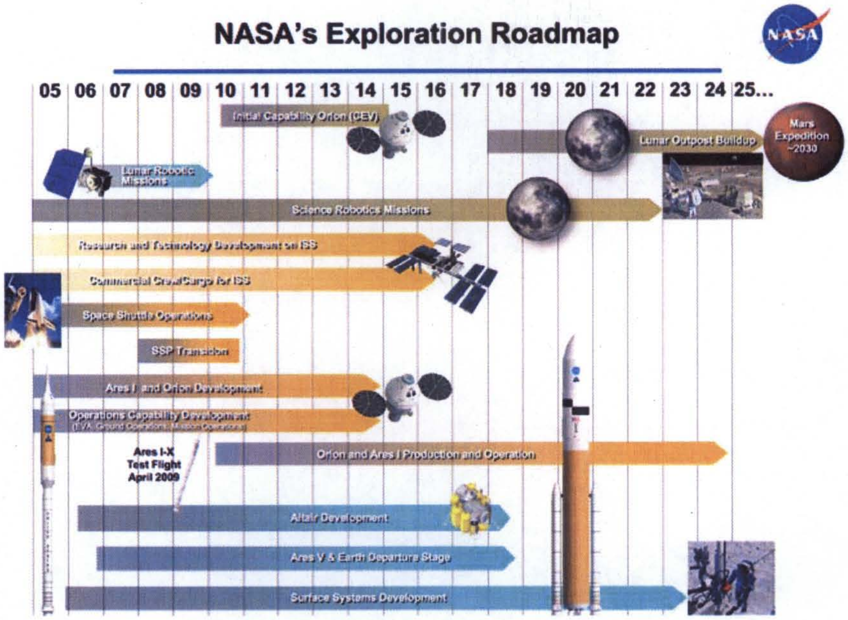

Figure 2. NASA's Exploration roadmap

NASA has charged the Constellation Program with the task of developing the mission and transportation architectures to accomplish the VSE goals. Liquid propulsion systems supporting the manned portion of these elements include the following:

- Orion crew exploration vehicle – crew module reaction control system (CM RCS), service module Orion Main Engine (OME), service module auxiliary reaction control system (RCS), and service module reaction control system (SM RCS)
- Ares I crew launch vehicle – J-2X upper stage engine, first stage roll control system (RoCS), upper stage reaction control system (ReCS), and the Ares I-X roll control system
- Ares V cargo launch vehicle – RS-68B core stage engine, J-2X upper stage/earth departure stage (EDS) engine, and EDS RCS
- Altair lunar lander – lunar orbit insertion/descent main engine, ascent main engine, and RCS for both stages

These propulsion systems build on a combination of heritage propulsion systems, including the J-2, RL 10, Space Shuttle Orbital Maneuvering Engine, RS-68, R-1E and R-4D, as well as key technology investments, such as throttling liquid oxygen (LOX)/hydrogen (H_2) pump-fed engines, cryogenic fluid management (CFM), LOX/methane (CH_4) propulsion, and selective component-level technologies needed for integrated systems to best meet the architecture needs.

Some Constellation propulsion needs closely resemble current hardware, such as the RS-68 for the Ares V core stage engine. Some propulsion elements, such as the J-2X upper stage engine, draw on decades of experience to adapt heritage hardware to the more demanding Constellation requirements. Other Constellation needs require significant advancements in key liquid propulsion technologies to raise the technology readiness levels (TRL) to TRL 6 (demonstrated in a relevant environment) at least by the applicable vehicle preliminary design review (PDR) dates. The current lunar exploration architecture has set goals and mission objectives that necessitate using new systems and extending existing technologies beyond their present applications. In the near term, the majority of these technologies result from the need to apply high-performing cryogenic propulsion systems to long-duration, in-space applications. Advanced cryogenic propulsion is crucial to these applications if they are to have systems that reduce vehicle mass, enhance the safety of vehicle systems and ground operations, and provide a longer-term path for in-situ resource utilization (ISRU). These liquid propulsion-related technology investments are funded through NASA's Exploration Technology Development Program and managed by the Propulsion and Cryogenics Advanced Development (PCAD) and CFM offices. NASA, partnering in many cases with industry and academia, is developing these key propulsion technologies to enable the implementation of the plan to take man to the Moon, Mars, and beyond.

II. Orion

The Orion crew exploration vehicle (CEV) consists of four major sections – the Launch Abort System (LAS) for emergency crew escape, the Crew Module (CM) housing the pressurized crew compartment, the Service Module (SM) containing the majority of life support, main propulsion/attitude control, thermal control, and power generation hardware, and the Spacecraft Adapter (SA) for structural transition to the launch vehicle (Figure 3). All Orion liquid propulsion elements are in the CM and SM.

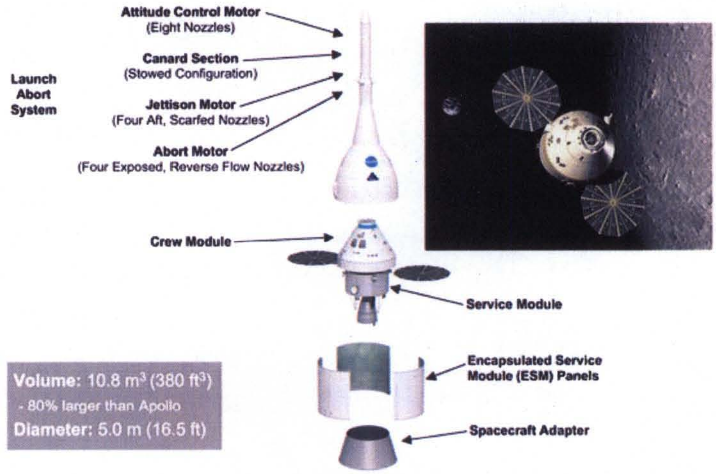

Figure 3. Expanded view of Orion sections

For Orion propulsion, NASA initially baselined the use of LOX/CH_4 for the SM and gaseous oxygen (GOX) with either a liquid or gaseous hydrocarbon for the CM. LOX/CH_4 offered performance benefits over traditional storables and had the strongest potential for synergy with ISRU on the Moon and Mars. It gave NASA the ability to get near-term experience with using in-space cryogenic propulsion systems prior to long duration lunar flights and ISRU synergy for later parts of the architecture. The CM propulsion has a very small impulse requirement and a long duration inactive requirement. A GOX-based system has the advantages of being Earth storable, commonality with the life support system, and non-toxic when combined with alcohol or methane.

However, to minimize the gap between retirement of the Space Shuttle and Orion introduction for supporting ISS, the use of LOX/CH_4 for the SM was deemphasized. With the selection of Lockheed Martin as prime contractor, the Orion baseline became GOX/CH_4 for the Crew Module, and nitrogen tetroxide (NTO)/monomethyl hydrazine (MMH) for the Service Module.

The CM RCS, shown in Figure 4, is used for maneuvering the capsule in space for heat-shield-forward attitude prior to atmospheric entry, as well as dispersion control during a skip entry (Kepler) maneuver, which is used to get to the downrange landing site. The CM RCS is also used within the atmosphere for bank angle modulation and attitude rate dampening prior to drogue parachute deployment. Finally, the CM RCS can be used, if needed, for both landing orientation under the parachutes prior to touchdown and for control during a LAS abort after separation from the solid fuel escape rocket.

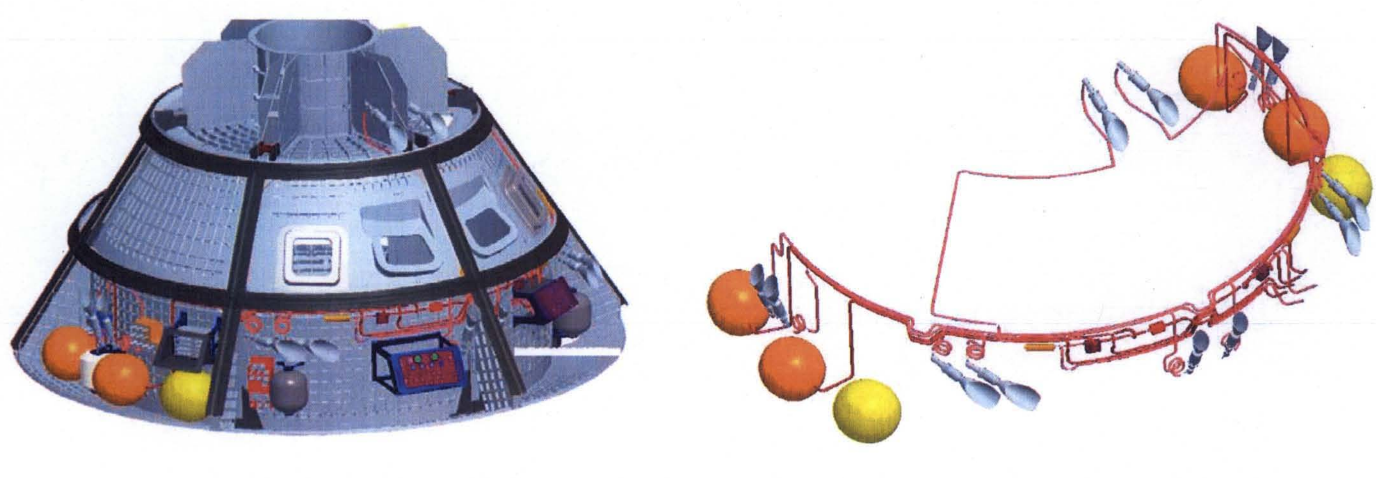

Figure 4. CM showing placement of RCS propulsion, left, and separate, right, for clarity.

The original CM RCS baseline used GOX/GCH_4 stored in high-pressure carbon composite over-wrapped pressure vessels and then regulated down to feed 712 Newton (N) thrusters which used a spark ignition system. During a vehicle weight scrub activity, the decision was made to go to a monopropellant hydrazine system because the mass fraction of hydrazine offsets the performance benefits of GOX/GCH_4, and provides higher TRL propulsion components. The propellant mass based on the mission impulse is a small fraction of the propulsion system weight. Ongoing design maturation is centered on reducing the required thrust class to bring it into line with Aerojet's heritage MR-104 monopropellant thruster designs. In addition, hardware and ground controls are being matured to address the handlng of residual hydrazine after touchdown or in the case of an unplanned hard landing.

The Service Module propulsion system consists of one 33,362 N main engine based on an uprated Space Shuttle Orbital Maneuvering System (OMS) engine operating with higher mixture ratio (MR), chamber pressure and area ratio; eight 489 N thrust auxiliary apogee thrusters based on the Apollo R-4D operating at higher MR, chamber pressure, and area ratio; sixteen 111 N thrust RCS thrusters based on the Space Shuttle R-1E vernier thruster but using a shorter pulse width; 1 to 2 MMH tanks; 1 to 2 NTO tanks, and 4 helium pressurant tanks (Figure 5). Final design details are still in work.

The OME is sized to support high-altitude abort options going to ISS inclination. Once Orion completes missions supporting ISS, the OME total thrust requirement significantly decreases. The auxiliary apogee thrusters are used for small translational maneuvers, docking control, and as a backup for main engine failure. The RCS thrusters are used primarily for attitude control. The propellant storage and distribution system feeds all thrusters from common tankage.

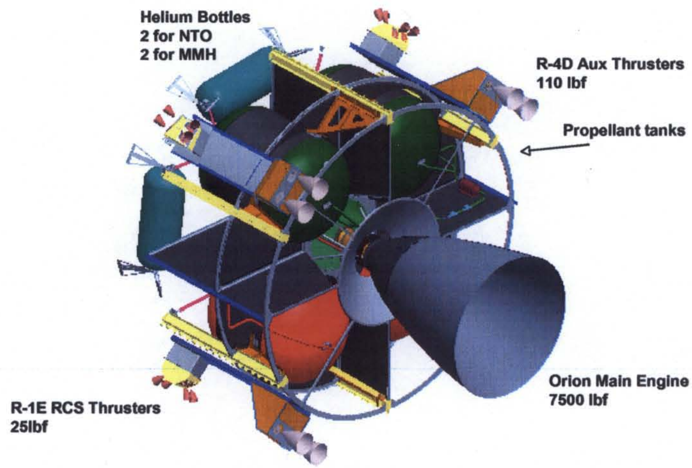

Figure 5. Service Module propulsion system.

III. Ares I

The Ares I crew launch vehicle is designed to carry the Orion CEV into low Earth orbit. The Ares I first stage main propulsion will be provided by a Space Shuttle-derived five-segment Reusable Solid Rocket Booster (RSRB), which is not addressed in this paper. The Upper Stage is a new development liquid hydrogen/liquid oxygen (LOX/LH_2) stage powered by the Apollo heritage derived J-2X engine. The first stage roll control and upper stage reaction control systems also use liquid propulsion components. Figure 6 shows the integrated Ares I, including its liquid propulsion components.

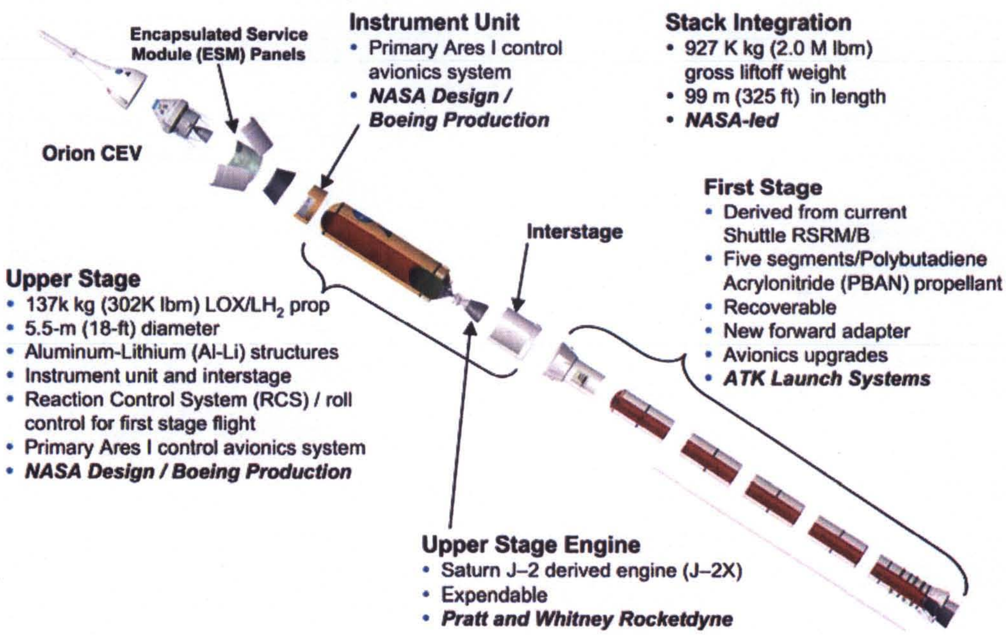

Figure 6. Expanded View of Ares I

A. J-2X Upper Stage Engine

The J-2X Upper Stage Engine (USE) is an excellent example of the Constellation Program's effort to use heritage hardware where possible to provide common hardware for the Ares I and Ares V. This streamlines hardware development and reduces program, technical and budget risks. Pratt & Whitney Rocketdyne (PWR) is developing the J-2X. For Ares I, the J-2X will provide second stage propulsion, igniting at an altitude of roughly 30,480 meters (m) and burning for approximately 500 seconds. Detailed J-2X requirements are summarized in Figure 7. The J-2X also provides upper stage propulsion for the Ares V, as discussed in Section IV.

Figure 7. J-2X Key Requirements.

The J-2 heritage LH_2/LOX gas generator design was selected as the operating cycle for the J-2X. The J-2X design also includes designs and knowledge from the RS-68, X-33 aerospike XRS-2200 engine, and development knowledge of the J-2S tap-off cycle engine. The Ares I and Ares V missions require that the J-2X operate at much higher temperatures, pressures, and flow rates than the heritage J-2, making it one of the highest performing gas generator cycle engines ever built, approaching the efficiency of more complex, staged-combustion engines like the Space Shuttle Main Engine (SSME).

Ares I mission requirements drive the J-2X thrust requirement, while Ares V requirements drive the engine's specific impulse performance. Both must be balanced against schedule, cost, weight, and volume constraints. Other changes reflect contemporary manufacturing techniques and materials, as well as post-Apollo engine design and analysis techniques.

The J-2's gas generator cycle could be stretched only so far. Designers realized that the greater thrust and specific impulse requirements would drive the design to a high-area-ratio nozzle. Weight and cooling concerns would result in a change from an all-metal nozzle to a regeneratively-cooled nozzle with a composite nozzle extension cooled by radiation and turbine exhaust gas. The current two-section nozzle extension will be the largest composite nozzle ever built and is one of the highest risk components associated with J-2X development.

Because propulsion is typically among the highest risk aspects of any new launch vehicle development, the J-2X team is proceeding on a very aggressive development and test schedule that includes early risk mitigation using heritage hardware, design risk mitigation prior to component testing, component and subassembly testing, and engine system testing. The engine team is proceeding toward Critical Design Review (CDR) in mid-2008, ahead of the rest of the Ares I vehicle.

The development plan includes testing in 2006 and 2007 of heritage injector, valve, inducer, and impeller hardware at NASA Marshall Space Flight Center. While that testing continues, workhorse gas generator testing is scheduled to begin in early 2008, using 43- and 61-element injectors to establish a final density and total number of elements for the full-scale injector.

NASA Stennis Space Center in Mississippi is supporting a range of higher-level engine testing that represents operation of the engine over its full 550-second mission duration. Following modifications of the A-1 stand in 2007 for sea-level testing, Power Pack 1A testing began in late 2007 and continues in 2008. The test article consists of heritage J-2 turbopumps and gas generator. These tests will reestablish baseline performance for the J-2 hardware and engine environments. The A-2 test stand, which currently supports the SSME, will be turned over to J-2X to support partial altitude engine testing in 2010 or 2011. Additionally, NASA broke ground in 2007 for a new A-3 stand, which will support altitude testing of J-2X engines beginning in late 2010. Plans are also under way for a main propulsion test article stand at Marshall Space Flight Center to test the J-2X engine integrated with a ground test version of the Ares I upper stage.

B. Ares I Reaction/Roll Control Systems
The Ares Upper Stage Project has assigned the responsibility for developing both the liquid-fueled Upper Stage (US) ReCS and the First Stage (FS) Roll Control System (RoCS), shown in Figure 8, to the Ares I Upper Stage Element.

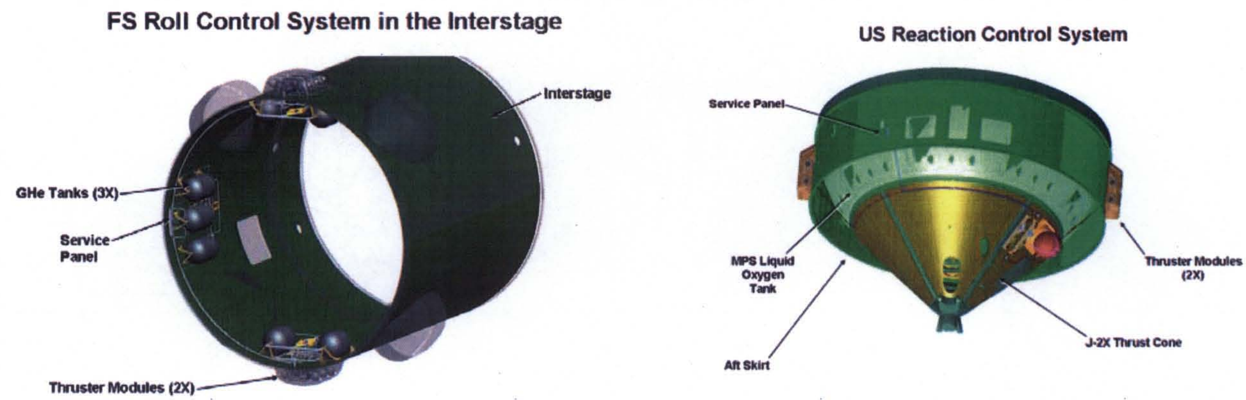

Figure 8. Conceptual layouts of the first stage roll control, left, and upper stage reaction control, right.

The FS RoCS will provide roll control capability during FS ascent until Upper Stage (US) separation. The reference configuration is a one degree of freedom (1-DOF), distributed, pressure-regulated hydrazine monopropellant system with localized propellant tanks, using 2780 N-class thrusters with a total usable propellant load of 499 kilograms (kg). The FS RoCS configuration has two RoCS thruster modules mounted on opposite sides of the Interstage structure. The system is designed to support firing multiple thrusters simultaneously as required to mitigate roll torque disturbances. Each thruster module contains six 2780 N thrusters.

To help mitigate the risk associated with the RoCS, NASA chose to award an advanced development contract to mature the design to a PDR plus level of maturity. In May 2007, NASA selected Aerojet-General Corp. to develop and test the engines for that effort. The RoCS system for the Ares I will be procured under the Upper Stage Production Contract.

The Upper Stage ReCS is a 3-DOF, distributed, blowdown hydrazine monopropellant system, using 534-400 N-class thrusters with a total usable propellant load of 13.6 kg. The Upper Stage RCS will provide 1-DOF roll control throughout the Upper Stage's operation, as well as 2-DOF pitch and yaw control when the J-2X upper stage engine is not in operation before Upper Stage ignition and between engine shutdown and Orion crew exploration vehicle separation from the Upper Stage. The ReCS has two thruster modules on the Upper Stage 180 degrees apart. The system is designed to support firings of multiple thrusters simultaneously for attitude control in multiple vehicle axes. Each thruster module contains six engines for 3-DOF attitude control. The thruster modules will be located on the Upper Stage aft skirt. Like the RoCS, the ReCS will be developed and procured under the Upper Stage Production Contract.

C. Ares I-X Roll Control
The first flight of Ares I, designated Ares I-X, will be a suborbital development flight test that will provide critical data about the flight dynamics of the integrated launch vehicle stack, as well as provide better understanding of stage separation and roll control. The Ares I-X Flight Test Vehicle (FTV) employs a combination of flight and mockup hardware, resulting in a vehicle similar in weight and mass to the operational vehicle. To initiate a 90-degree roll shortly after liftoff to orient the vehicle for flight and counteract vehicle- and aerodynamic-induced roll during ascent, Ares I-X will have an active NTO/MMH RoCS mounted on the Interstage structure. The engines will have tangential thrust components in opposite directions (along the Y axis of the vehicle's forward motion), with two to four engines providing clockwise thrust and two to four engines providing counter-clockwise thrust.

Ten stages of heritage PWR Peacekeeper Stage 4 missile assets were harvested from decommissioned U.S. Air Force assets for RoCS engines and propellant feed system components for Ares I-X . They are used for duty cycle testing at White Sands Testing Facility (WSTF), tanking and de-tanking tests at KSC, and the Ares I-X flight test vehicle planned for launch in April 2009. The RoCS completed its CDR in December 2007. NASA-sponsored operational verification testing of one of the salvaged Peacekeeper axial engines (AXEs) at WSTF was completed in April 2007. These tests verified the AXE's suitability for handling the anticipated Ares I-X roll control duty cycle. These tests also characterized the AXE's ability to handle hypergolic overpressures ("zots") due to gas ingestion. With much of the engine hardware already assembled, the primary effort of the RoCS team is focused on design and fabrication of the structures enclosing the engines within the Interstage.

IV. Ares V

The Ares V cargo launch vehicle will loft the Earth departure stage (EDS), carrying the Altair lunar lander, into LEO. Once Orion docks with Altair, the EDS will initiate a trans-lunar injection burn to head toward the moon. Ares V has also been considered for boosting large science payloads into LEO. Ares V will be approximately 110 m tall. It will deliver 128.8 metric tons (283,913 pounds) to LEO or 54.2 metric tons (119,521 pounds) to trans-lunar injection. The Ares V first stage propulsion system consists of a core stage powered by five commercial liquid hydrogen/liquid oxygen (LOX/LH_2) RS-68 engines, flanked by two five-segment solid rocket boosters based on the Ares I first stage. Atop the core stage, the EDS is powered by a single J-2X upper stage engine. Figure 9 shows the integrated Ares V, including its liquid propulsion components.

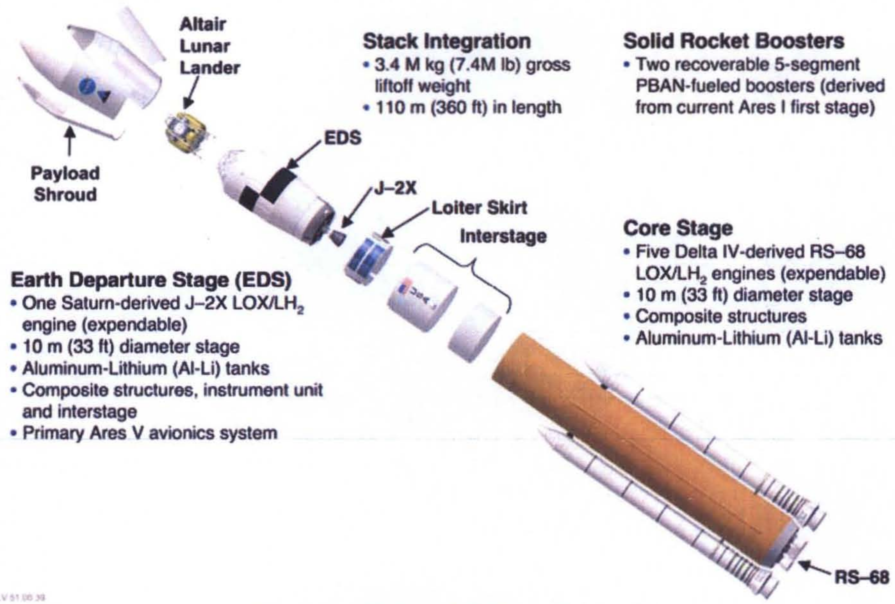

Figure 9. Expanded view of Ares V.

A. Core Stage Liquid Propulsion Systems

The present core stage main propulsion is provided by the PWR RS-68 engine. The design that resulted from the Exploration Systems Architecture Study (ESAS) in 2005 used a version of the RS-25 Space Shuttle Main Engine (SSME) modified to be expendable, receiving propellants from an 8.4 m core stage tank. At that time, the other main propulsion systems also included a 4-segment shuttle booster to supplement first stage propulsion and the RS-25 for upper stage propulsion. NASA design studies that followed the final ESAS report selected a 5-segment variation of the booster and an evolved version of the Apollo-Saturn-era J-2 engine – designated J-2X – for the upper stage propulsion, while retaining the RS-25 for the core stage. Follow-on engineering and business trade studies concluded that design, development, test, and engineering costs could be reduced and out-year savings realized by using the commercially available, expendable RS-68 engine, shown in Figure 10, for the Ares V core stage instead of the RS-25.

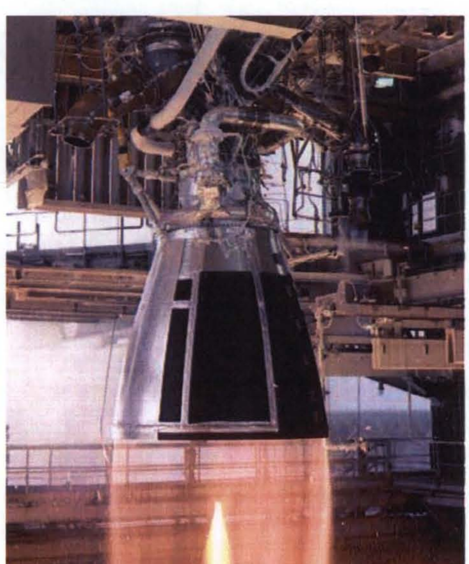

Figure 10. RS-68 during testing.

Developed for the U.S. Air Force Evolved Expendable Launch Vehicle program and flown on the Delta IV launch vehicle family, the RS-68 is the most powerful LOX/LH_2 booster engine in existence, capable of producing 2,891 kilonewtons (kN) of thrust at sea level, compared to 1,868 kN for the SSME. The ESAS had considered and rejected the RS-68 because its lower specific impulse (I_{sp}) and size were not compatible with the 8.4 m core stage propellant tank and payload requirements for the Ares V. The ESAS concluded that the high performance RS-25 SSME could be made expendable to reduce manufacturing costs by half. However, subsequent analyses showed that the RS-68, modified to meet NASA requirements, would cost significantly less than a modified SSME, a potential savings magnified by the use of five main engines on each core stage. Studies showed that the cost, technical, schedule, and safety risks of redesigning the RS-25 were greater than the risks associated with scaling up the core stage tank to 10 meters in diameter to hold additional propellants for the less efficient RS-68 and make room for the larger engine.

To meet NASA's needs, the current RS-68 requires several changes, including increases in specific impulse and thrust, which are the subjects of a current Air Force-managed upgrade program designated RS-68A. NASA is additionally pursuing changes for increasing exhaust nozzle life from 250 seconds to 327 seconds for the longer EDS operation time, reducing the presence of free hydrogen around the launch pad during engine start, and reducing Ares V's use of helium because it is a nonrenewable and increasingly expensive resource. This engine variant is referred to as RS-68B.

Full-scale development work on Ares V was not scheduled to begin until late calendar 2010. However, initial seed money provided by Congress for the Ares V allowed NASA to begin early planning and design work in 2006. This work largely focused on the core stage and the RS-68B. The Ares V Project completed an Upgrade Requirements Review in October 2006 and managed a series of subscale tests in 2006 and 2007 that helped establish the optimum element density for both the RS-68B and the J-2X main injectors. It also allowed fabrication of hardware for the helium spin start. The free hydrogen issue was quantified by PWR with a detailed computational fluid dynamics analysis of the stage at liftoff. The Ares Project is continuing to develop the Ares V. Internal NASA design studies continue to evaluate options to increase the Ares V payload, including the addition of a sixth RS-68 to the core stage engine cluster and operating at a 108 percent power level. The Air Force RS-68A upgrades have completed CDR and are scheduled to go into development testing in fall 2008.

B. Earth Departure Stage Liquid Propulsion Systems

Work on the EDS remains at an early stage, with the focus primarily on refining EDS concepts and understanding requirements and Constellation systems engineering issues. The EDS will be powered by a single J-2X. For Ares V, the J-2X will provide an engine start at altitude, operate for approximately 500 seconds for second stage propulsion, shut down, perform on-orbit loiter for up to 5 days, restart on-orbit upon command, operate for roughly 300 seconds in secondary mode at reduced thrust level to execute trans lunar injection (TLI), and perform final engine shutdown. The primary-mode oxidizer-fuel mixture ratio is 5.5, while secondary-mode uses a mixture ratio of 4.5 to deliver roughly 82% of primary-mode thrust. Primary-mode thrust will be used for the ascent burn on both Ares I and Ares V. Secondary thrust mode is for the Ares V's TLI burn due to load limitations on the Orion-to-lunar lander docking system.

The implementation and verification of Ares V design requirements are currently under discussion and analysis. The requirements remain in flux due to the immature state of the overall Ares V and EDS concept, mission, and design. Ares V and EDS orbital parameters, induced environments, and acceptable safety risks remain undefined. Some of the Ares V design requirements for J-2X, such as secondary mode operation, impact the design on such an intrinsic level that they must be considered part of the basic development of the engine. Other design requirements, such as on-orbit thermal environments, will be partially deferred for detailed design until better, more mature definition for the lunar mission is completed. The full slate of J-2X requirements for Ares V will be verified during integrated EDS environments testing. J-2X design changes to fulfill the lunar mission may consist of modifications to existing hardware, with a focus on upgrade kits to be added to the baseline Ares I upper stage engine.

C. Reaction Control System

The maturity of the RCS for the EDS remains at a very preliminary stage, focused entirely on requirements issues. Among those are vehicle orientation during the loiter period between EDS orbital insertion and the rendezvous of the Orion spacecraft. The Orion and Altair designs prefer a sun-pointing mode for minimum thermal effects and optimum solar power generation and communications performance. Pointing for solar power is particularly significant. The EDS/Altair/Orion stack, however, exhibits a natural preference for gravity gradient (Earth-pointing) mode. Maintaining a sun-pointing attitude would impose a weight penalty of up to 4,082 kg for the additional propellants required for station-keeping. Analysis suggests that the addition of fuel cells/batteries to the EDS with a power interface to Orion would impose a lesser weight penalty than the additional propellants for RCS. Analyses are expected to continue as the Ares V design is refined.

V. Altair

The two main goals for NASA's Altair in-house design team are to develop enough insight into the design to produce and validate a good set of requirements and also to pursue an approach for early project development that will allow a more streamlined Phase A/B design process and a better defined production contract.

Key tenets of NASA's approach include: (1) a multi-center team leveraging the strengths of all 10 NASA centers and multiple industries, (2) looking for new, non-traditional ways of doing business, (3) simple and elegant solutions rather than sophisticated and complex, (4) starting with the minimum functional solution and adding requirements only as necessary, and (5) making a conscious effort to buy down technical, programmatic, and cost risk.

As part of its in-house design work, NASA has established a minimum functionality (and minimum weight) design baseline, with no consideration for contingencies or added redundancy. It is not a flyable design, but it does provide early, critical insight into the overall viability of the architecture and a starting point to make informed cost/risk trades to consciously buy down risk. From this minimum functionality design starting point, the in-house NASA design team has looked at safety and reliability upgrades required for a minimum flyable vehicle and is now addressing additional upgrades to this vehicle. In parallel, they have engaged multiple industry design teams to assess and provide feedback on their minimum functionality design and offer safety and reliability recommendations for a flyable vehicle. NASA will then identify the biggest risks in the design and assess optimum ways to mitigate them. They will take the best ideas and information from their in-house and contractor efforts to baseline their plan forward and build hardware/test beds in the 2009-2011 timeframe to mature key design components and lower the risk of unknown surprises. Propulsion trades and analyses completed to date by NASA include the descent module engine performance characteristics, the number of descent module engines, and tank pressurization concepts. Analyses that are still open include ascent module propellant selection, RCS propellant selection, cryogenic fluid management, fluid management for center of gravity control, post-landing operations for hypergolic systems, and engine pre-start chill-down. To date, the top three lander technology priorities identified by NASA are liquid propulsion related. They include a high reliability LOX/H_2 throttling engine, cryogenic fluid management (for up to 6 months on the moon's surface), and a LOX/CH_4 ascent main engine.

Altair has three unique design reference missions: lunar sortie crew, lunar outpost crew, and lunar cargo. The goal is to have a single lander design that is configurable to support all three of these missions. All missions have common descent propulsion components and the sortie and outpost missions have a common 'minimized' ascent module with a common ascent propulsion system.

Within the confines of ITAR restrictions and overall NASA headquarter guidelines for the VSE roles and responsibilities, NASA and its prime vehicle contractor(s) will look at all available options, both foreign and domestic, in making component and engine decisions.

For the descent module, the minimum functionality propulsion system (Figure 11) consists of a single throttleable restartable 82,857 N LOX/LH_2 main engine, 4 LOX tanks, 4 LH_2 tanks, 4 Helium (He) tanks and 16 445 N NTO/MMH RCS thrusters with a dry mass of 2,510 kg. LOX/H_2 propellants were selected as an enabling technology to meet the lunar lander weight budget.

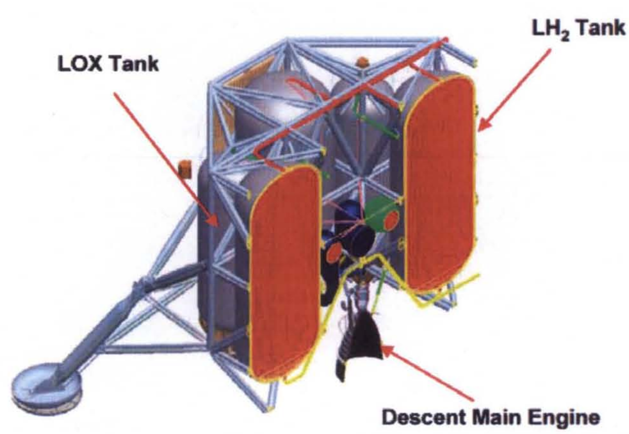

Figure 11. Altair descent module propulsion system

The descent main engine is a single 3.3:1 throttleable pump-fed main engine capable of multiple restarts. This engine is used in the Constellation architecture for both lunar orbit insertion and descent to the surface of the moon. Original sizing studies showed an optimal descent thrust was 124,600 N, but 82,857 N was selected because of the lower development risk and cost. Also, a single engine configuration was chosen due to NASA's minimum functionality paradigm. To date, NASA has provided technology funding to two contractors, PWR and Northrop Grumman, to mature this engine technology, demonstrate deep throttling capability, and generally raise the TRL to 6. Under PWR's Common Extensible Cryogenic Engine (CECE) contract, an RL 10 has been modified and successfully demonstrated to 11.4:1 throttling. Planned NASA/contractor descent main engine work over the next two years will include investments in an operable high performance/deep throttling CECE and pintle variable area injector technology. In addition, NASA MSFC has also initiated a project to build a pump-fed 40,034 N battleship LOX/H_2 test bed to retire risks should the flyable lander descent main engine configuration change to a multiple engine design.

For the LH_2 and LOX tanks, spray on foam insulation and variable density multi-layer insulation are planned to minimize boil-off on the launch pad and optimize performance for both ground and space environments. The four helium pressurant tanks are composite overwrap pressure vessel construction.

The minimum functionality descent module RCS is baselined using MMH/NTO, but NASA continues to consider both LOX/ethanol and LOX/H_2. Four thruster quads will contain 16 445 N engines. One MMH tank and one NTO tank are equally sized, with anti-slosh and propellant management devices comprising about 20% of the tank mass. There is also one composite overwrap helium pressurant tank sized explicitly for isothermal and isentropic conditions.

For the ascent module propulsion system, the minimum functionality propulsion system (Figure 12) consists of a single 24,475 N pressure-fed engine, 16 445 N RCS engines (notionally common to descent module) in four quads, 2 MMH tanks, 2 NTO tanks and 4 He pressurant tanks.

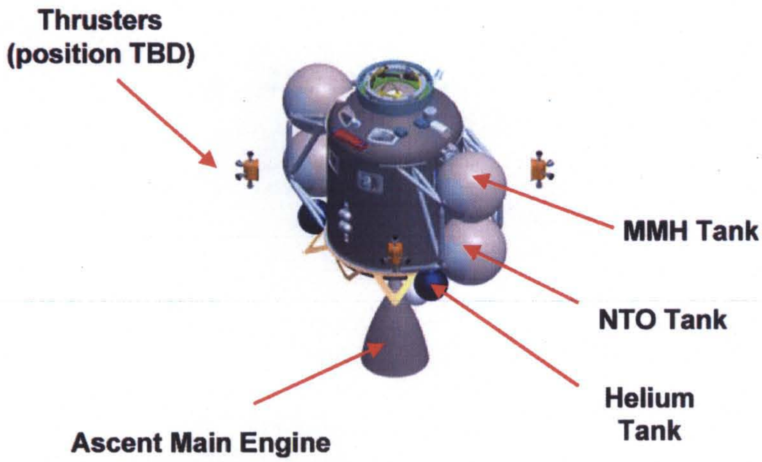

Figure 12. Altair ascent module propulsion systems.

The ascent module propellant tanks are built of titanium and are shared between the main engine and RCS thrusters.

The ascent main engine is a single, non-throttleable, restartable fixed thrust vector engine. Although the design is notionally baselined for hypergolic propellants (derived from the Shuttle orbital maneuvering engine and RS-18 Apollo Lunar Ascent Module engine), NASA is continuing a parallel investment in LOX/CH_4 engine technology to see if the readiness level can be raised to where it can be baselined with its higher performance and longer term ISRU benefits. NASA has developed ascent module designs for both storable propellants and LOX/CH_4.

Recent NASA MSFC LOX/CH_4 injector tests have demonstrated adequate performance to achieve the desired LOX/CH_4 engine performance levels. As a result, NASA has confidence that a technology demonstrator engine will provide high performance for a representative mission duty cycle within the next 21 months. An award for this contract is planned in April 2008. NASA also continues to invest in other key technologies to retire LOX/CH_4 related risks associated with the ascent module and raise the overall TRL. Benefits of LOX/CH_4 to the ascent module over hypergols include lower weight (400-800 lbs. mass over prior Constellation Study findings), lowest life cycle cost and comparable reliability and schedule. NASA's funding of LOX/CH_4 related technologies with industry partners includes:

- Reaction control engine technologies with Aerojet, Alphaport, Firestar Engineering, Northrop Grumman Space Technologies, Pratt & Whitney Rocketdyne, and WASK
- Ascent main engine technologies with Armadillo, ATK/GASL, KT Engineering, Orion Propulsion Inc., Plasma Processes Inc., Pratt & Whitney Rocketdyne, and XCOR

In addition, NASA is funding related in-house technology and facility projects including enhanced combustion performance tests on a main engine sized injector, and modification of WSTF's Test Stand 401 for integrated RCS, main engine and feed system testing at altitude.

VI. Summary

In summary, liquid propulsion for Project Constellation is well on its way. Significant progress has been made since its inception in late 2005. J-2X is completing its critical design review early this summer, Orion propulsion systems are under contract with the vehicle-level PDR recently completed, and technology/development programs are in process for Ares I roll control and RCS, Ares V booster, and Altair propulsion systems. To minimize cost, technical, and schedule risks, NASA is making extensive use of heritage hardware approaches and lessons learned from past programs. America's exploration journey continues on a path to bring man back to the Moon, one step at a time.